

A study of charm quark correlations in ultra-relativistic $p + p$ collisions with PYTHIA

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(Dated: July 3, 2015)

Abstract: Measurements of heavy flavor quark (charm and bottom) correlations in heavy ion collisions are instrumental to understand the flavor dependence of energy loss mechanisms in hot and dense QCD media. Experimental measurements of these correlations in baseline $p+p$ collisions are crucial to understand the contributions of perturbative and non-perturbative QCD processes to the correlation functions and further help in interpreting correlation measurements in heavy ion collisions. In this paper, we investigate $D-\bar{D}$ meson correlations and D with one particle from D meson decay daughter correlations using PYTHIA Event Generator in $p + p$ collisions at $\sqrt{s} = 200, 500$ and 5500 GeV. Charm/bottom events are found to contribute mainly to the away side/near side pattern of D -electron correlations, respectively. In the energy region of RHIC, $D-\bar{D}$ correlations inherit initial $c-\bar{c}$ correlations and $B \rightarrow DX$ decay contribution is insignificant. Furthermore, Bottom quark correlations are suggested to be applicable at LHC energy, as the bottom contributions on D related correlations are relatively large.

PACS numbers: 25.75.-q, 25.75.Cj

I. INTRODUCTION

Experimental observables indicate that strongly coupled Quark-Gluon Plasma (sQGP) is formed in the high energy heavy ion collisions [1–4]. Heavy quarks (c and b) serve as good probes to study the properties of sQGP, as charm and bottom can only be pair-produced in early stage hard scatterings due to the large mass (> 1 GeV/ c^2) [5]. Experimental measurements have shown that heavy quarks suppression at relatively high- p_T is as large as that of light quarks [6, 7], which was inconsistent with earlier theoretical expectation of the flavor dependence of parton energy loss. Thus it is crucial to understand the charm-medium interaction mechanism. Recently, the azimuthal correlations of heavy quarks are found to have the potential for distinguishing different energy loss mechanisms inside the hot medium [8, 9]. The theoretical prediction indicates that pure radiative energy loss does not change the initial angular correlation function in a significant way, whereas pure collisional energy loss is more efficient at diluting initial back-to-back charm pair correlation, this could even lead to a peak in the near side at low- p_T [11]. To approach the azimuthal correlations of heavy quarks in experiment, measurement of $D-\bar{D}$ correlations is the ideal candidate [10, 11], as $D-\bar{D}$ correlations inherit most of charm pair correlations. However, due to the relatively small charm cross section, small hadronic decay branching ratio which is used to reconstruct D meson and limited signal to background ratio, the direct measurement of $D-\bar{D}$ correlations would be very challenging. One has to consider use $D-X$ or $X-D$ correlation measurement instead of direct $D-\bar{D}$, where X is a decay daughter of D meson.

Considering only leading order perturbative Quantum

Chromodynamics (pQCD) processes, the initial charm pairs exhibit exactly back-to-back correlation. High order pQCD processes broaden the initial charm correlations. Charm quarks finally fragment into charmed hadrons, the non-perturbative fragmentation processes further broaden the correlations. In the case of $D-X$ or $X-D$ correlation, decay kinematics and random combinatorial pairs would dilute or even destroy the correlation signal originating from initial charm pair correlations. It is crucial to understand these effects on the correlation function firstly in $p + p$ collisions which serve as the baseline for heavy ion collisions. Furthermore, an experimental measurement of $D-\bar{D}$ and $D-X$ ($X-D$) correlations in $p + p$ collisions would constrain the contributions from high order processes of pQCD calculations and non-perturbative fragmentation processes. In this paper, we utilize PYTHIA Event Generator (EG) to study $D-\bar{D}$ and $D-X$ ($X-D$) correlations in $p + p$ collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies, $\sqrt{s} = 200, 500$ and 5500 GeV.

The rest of the article is organized in the following way: Section II summarizes the details of tuning PYTHIA parameters. In Sec. III, we present the correlations results of $D-\bar{D}$ and $D-X$ ($X-D$). The comparison is made between RHIC and LHC energies. Last a summary is presented in Sec. IV.

II. PYTHIA TUNE

PYTHIA8 (version8.168) has been used in this study. In the following, we will use PYTHIA representing PYTHIA8. We tuned PYTHIA parameters to match the $c\bar{c}$ production cross-section as inferred from measure-

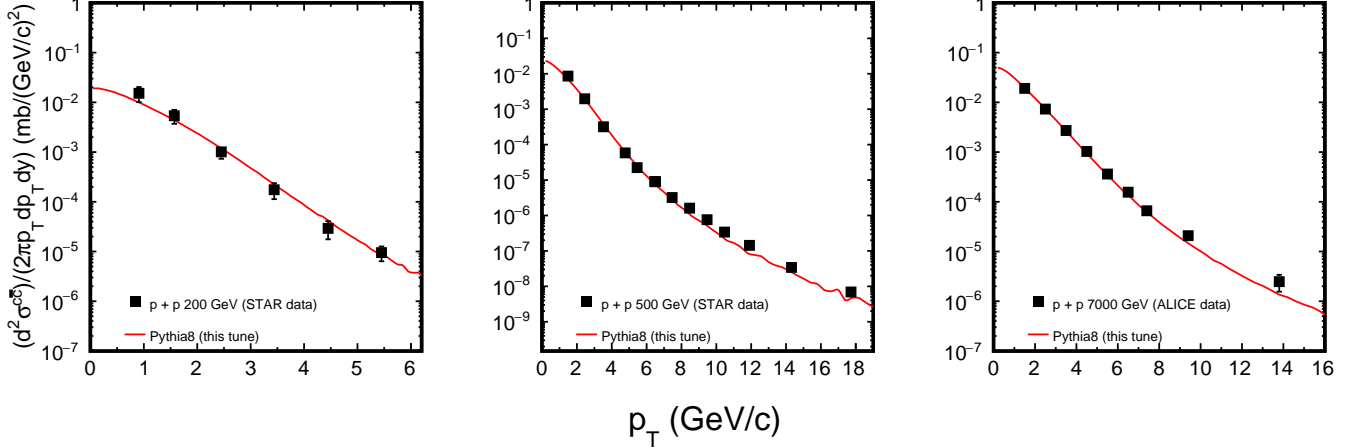


FIG. 1: (Color online) $c\bar{c}$ production cross section as a function of transverse momentum in $p + p$ collisions at $\sqrt{s} = 200, 500$ and 7000 GeV from STAR and ALICE experimental data (solid squares) and tuned PYTHIA (red lines).

ment of D^0 and D^* production in $p + p$ collisions at $\sqrt{s} = 200$ and 500 GeV measured in the STAR experiment at RHIC [12, 13] and 7000 GeV measured in the ALICE experiment at LHC [14]. The choice of modifying the strong interaction coupling constant (α_s) value of final parton shower (TimeShower:alphaSvalue) and minimum invariant transverse momentum (p_T) threshold for hard QCD process (PhaseSpace:pTHatMin) gives the best χ^2/ndf to the data. Figure 1 shows the $c\bar{c}$ production cross section as a function of p_T from STAR measurement and PYTHIA. In the PYTHIA calculation, all ground state charm hadrons ($D^0, \bar{D}^0, D^+, \bar{D}^-, D_s^+, \bar{D}_s^-, \Lambda_c^+, \bar{\Lambda}_c^-$) were added together in the rapidity window $|y| < 1$ to obtain charm cross-section. The parameters of ‘TimeShower:alphaSvalue’ and ‘PhaseSpace:pTHatMin’ were set to 0.18 and 1.3 GeV/c for $\sqrt{s} = 200$ GeV collisions. These two parameters were set to 0.15 and 1.5 GeV/c for $\sqrt{s} = 500$ GeV collisions; 0.15 and 2.8 GeV/c for 7000 GeV. The χ^2/ndf values are 1.31 for 200 GeV data, 2.13 for 500 GeV data and 1.95 for 7000 GeV data, respectively. As lack of $p + p$ experimental data in top energy of heavy ion collisions at LHC (5500 GeV), the same setup of parameters as 7000 GeV was applied in PYTHIA simulation.

III. CORRELATIONS

$D-\bar{D}$ correlations are the ideal experimental way to study the azimuthal correlations of initial $c-\bar{c}$ pairs, as the charm quark mostly fragment to D mesons. In this paper, we use D to represent the combination of D^0, D^+, D_s^+ and \bar{D} to represent $\bar{D}^0, \bar{D}^-, \bar{D}_s^-$. In experiment, D mesons can be reconstructed by the hadronic decay channels. Figure 2 shows the $D-\bar{D}$ correlations in $p + p$ collisions at $\sqrt{s} = 200$ GeV for (a) real pairs and (b) all pairs. Where real pairs mean $D-\bar{D}$ from $c-\bar{c}$ pairs, all pairs mean

all possible $D-\bar{D}$ pairs in an event. A phase space cut of pseudorapidity ($|\eta| < 1$) was applied to match the typical STAR experimental acceptance. The integral of all the correlation functions were normalized to one, as we are interested in the correlation patterns here. The $D-\bar{D}$ azimuthal correlation function exhibits a clear away side correlation inherited from the initial $c-\bar{c}$ pair production. In case we only consider the leading order (LO) pQCD contribution, the $c-\bar{c}$ would show a delta function like away side correlations. The next-to-leading (NLO) order pQCD contributions including radiative corrections, flavor excitation and gluon splitting broadens the correlation function. There are no exact NLO pQCD calculations in PYTHIA, but the initial and final parton shower procedure emulates these effects. Thus some aspects of the multiple parton emission phenomenon could be well reproduced [15, 16]. The non-perturbative fragmentation process further broadens the correlation function. In other words, the correlation function of $D-\bar{D}$ inherits the initial $c-\bar{c}$ back-to-back correlation broadened by higher order pQCD and fragmentation processes. The results of all pairs in panel (b) are consistent with real pairs in panel (a), because most events only contain one $D-\bar{D}$ pair with phase space cuts ($|\eta| < 1$) in $p + p$ collision at RHIC energies. The experimental measurement of $D-\bar{D}$ correlations in $p + p$ collisions is crucial to constrain the higher order pQCD and fragmentation calculations. Further in the heavy ion collision system, Au + Au for example, the initial away side correlation is expected to be by the charm-medium interactions. Different energy loss mechanisms, collision energy loss or radiative energy loss, show dramatically different modification [8, 9]. The experimental measurement of $D-\bar{D}$ correlation in heavy ion collision system will help us to disentangle the question on charm quark energy loss mechanism. However, it is a quite challenging analysis, the statistics are limited by the small $c-\bar{c}$ production cross section, the usable

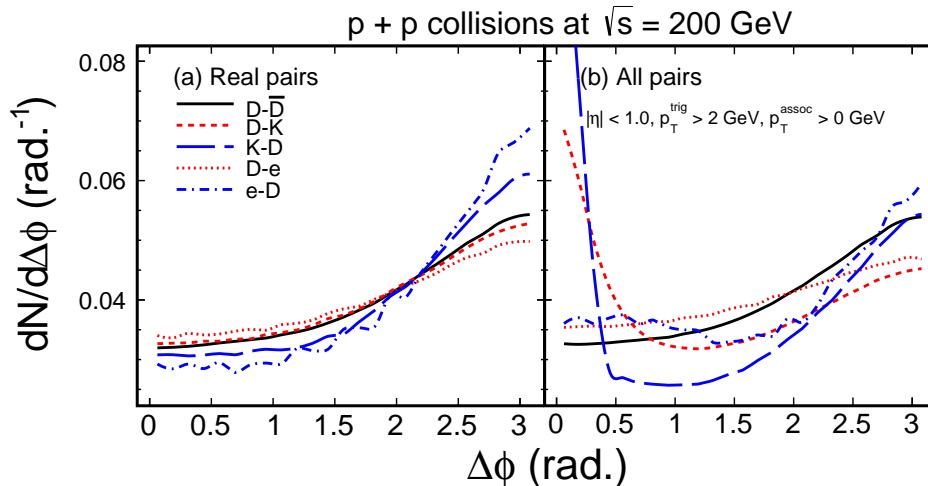


FIG. 2: (Color online) The $D\bar{D}$, DK , KD , De and eD correlations as a function of relative azimuth angle $\Delta\phi$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV in PYTHIA for (a) real pairs (pairs are from $c\bar{c}$ pairs), b) all pairs (all possible pairs in an event). The phase space cut is pseudorapidity ($|\eta| < 1$). An additional p_T cut is applied to trigger particles. The integrals of correlation functions are normalized to one.

hadronic decay branch ratio (e. g. $D^0 \rightarrow K^- + \pi^+$) and the limited signal over background ratio of reconstructed D mesons [12].

A. D - X (X - D) correlations

Instead of direct $D\bar{D}$ analysis, D - X or X - D correlations are other options to approach charm quarks correlations, where D - X means correlations of $D(\bar{D})$ meson and a decay daughter of $\bar{D}(D)$ meson (electrons, kaons, pions and so on). (First letter indicates the trigger particle.) The typical choices would be charged kaons and electrons. Charged pions are not good candidates, because of the copious production and resonance decay contributions to pions. Electrons could be divided into photonic and non-photonic electrons. Photonic electrons include those from γ conversion and Dalitz decay, while non-photonic electrons include those from charmed and bottomed hadrons semileptonic decays [6, 7]. Experimentally, non-photonic electrons can be statistically subtracted from inclusive electrons [6, 7]. Thus in the PYTHIA simulation results in Fig. 2, we use non-photonic electrons for D - e and e - D correlations. Also shown in Fig. 2 are D - K and K - D correlations. Panel (a) shows the correlation function inheriting from initial $c\bar{c}$ pairs. The away side correlations can be seen for all combinations. For $D\bar{D}$, DK and De , the different widths of away side peak are due to the decay smearing of $D \rightarrow K$ or $D \rightarrow e$. The different widths of away side peak of $D\bar{D}$, KD and eD are because minimum trigger p_T cut on D decayed particles (> 2 GeV/ c) actually requires higher p_T D mother trigger particles. Panel (b)

shows the correlation function for all possible pairs in an event. The large near side peak for DK and KD correlation are mainly due to the jet correlation, as most kaons are not from D decays. It suggests D - inclusive-hadron correlations are not good candidates to study the charm correlations. eD correlation also shows a near side correlation pattern, which is due to the semileptonic decay of B contribution. The STAR measurement indicates that ratio of non-photonic electrons from B to those from D is 0.2 at $p_T = 2$ GeV/ c [17]. The random pairs which do not originate from the same $c\bar{c}$ pair cause additional combinatorial background. It is partly the reason why the away side correlation width of D - e is wider than that of $D\bar{D}$. We also found tighter or looser cut on minimum transverse momentum of associate particle does not change the correlation patterns dramatically.

B. Components of $D\bar{D}$ correlations

The $D(\bar{D})$ mesons consist of directly produced $D(\bar{D})$ and $D(\bar{D})$ from $B(\bar{B})$ meson decays. To study the B contribution to the $D\bar{D}$ correlation function, we separate the $D\bar{D}$ pair combination into four cases: 1) direct D and \bar{D} , 2) D from B decays and \bar{D} from B decays, 3) D from B decays and direct \bar{D} , 4) direct D , and \bar{D} from B decays. The combination of case 2) + 3) + 4) is generally called $D\bar{D}$ pairs from B decays. Figure 3 shows the decomposed $D\bar{D}$ correlations in $p + p$ collisions at $\sqrt{s} = 200$ GeV ((a) and (b)) and 500 GeV ((c) and (d)) for two sets of trigger particle minimum p_T cut. It can be observed that the B decay contribution to $D\bar{D}$ depends on trigger particle p_T cut and collision energy.

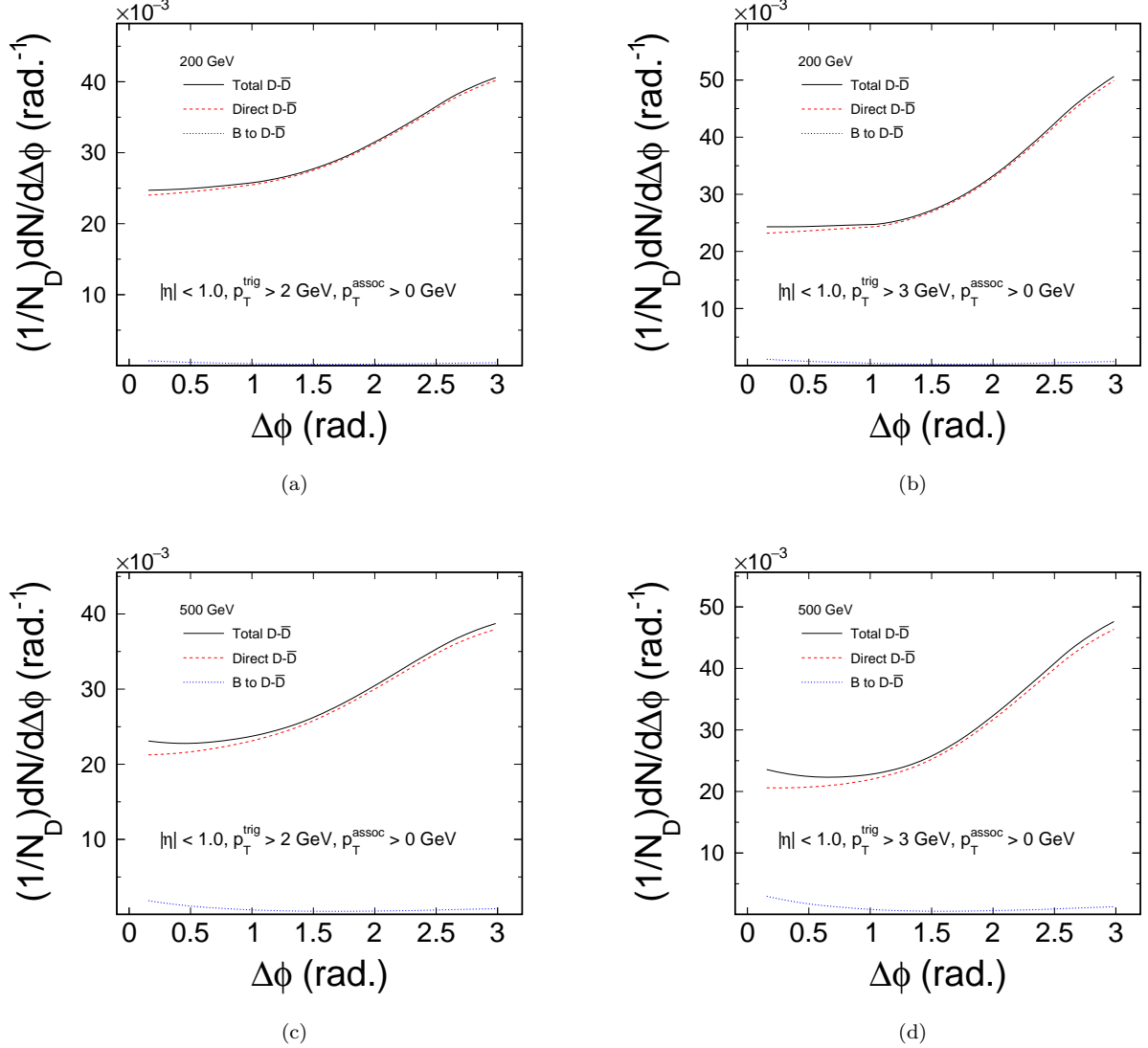


FIG. 3: (Color online) The $D\bar{D}$ correlations from different sources as a function of relative azimuth angle $\Delta\phi$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV (panel (a) and (b)) and 500 GeV (panel (c) and (d)). The minimum trigger p_T cuts are set to 2 GeV/ c (panel (a) and (c)) and 3 GeV/ c (panel (b) and (d)). The correlation functions are normalized by the number of D mesons.

The higher trigger particle p_T cut or collisions energy, the larger contribution from B decay. In comparison to direct $D\bar{D}$ pairs, $D\bar{D}$ pairs from B decays are insignificant. In $p + p$ collisions at $\sqrt{s} = 500$ GeV, with $p_T^{\text{trig}} > 3$ GeV/ c cut, the $D\bar{D}$ pairs from B decays are $\sim 4\%$ of the total $D\bar{D}$ pairs. As shown in the panel (d) of fig. 3, the B contributions cause the small near side correlation pattern of the total $D\bar{D}$ correlation. In $p + p$ collisions at $\sqrt{s} = 200$ GeV, even with $p_T^{\text{trig}} > 3$ GeV/ c cut, the contribution from B decays is still not sizable. It is also found that tighter or looser cut on minimum transverse momentum of associate particle does not change the conclusion. It indicates the $D\bar{D}$ correlations mostly inherit from $c\bar{c}$ pair production at RHIC energies. The effect of B decays on $D\bar{D}$ correlations is insignificant.

C. D - e correlations

D -electron (D - e) correlations contain contribution from different sources, thus it is more complicated than $D\bar{D}$ correlation. The inclusive electrons consist of photonic electrons and non-photonic electrons. The photonic electrons are from γ conversion (in experiment) and Dalitz decay (e. g. π^0, η), where the non-photonic electrons are from semileptonic decay of charmed and bottomed hadrons. The non-photonic electrons can be statistically separated from the inclusive electron samples in experiment [6, 7] which makes the D and non-photonic electron correlation measurement possible. Figure 4 shows the D^0 - e correlations from different electron sources in PYTHIA. Following the typical experimental

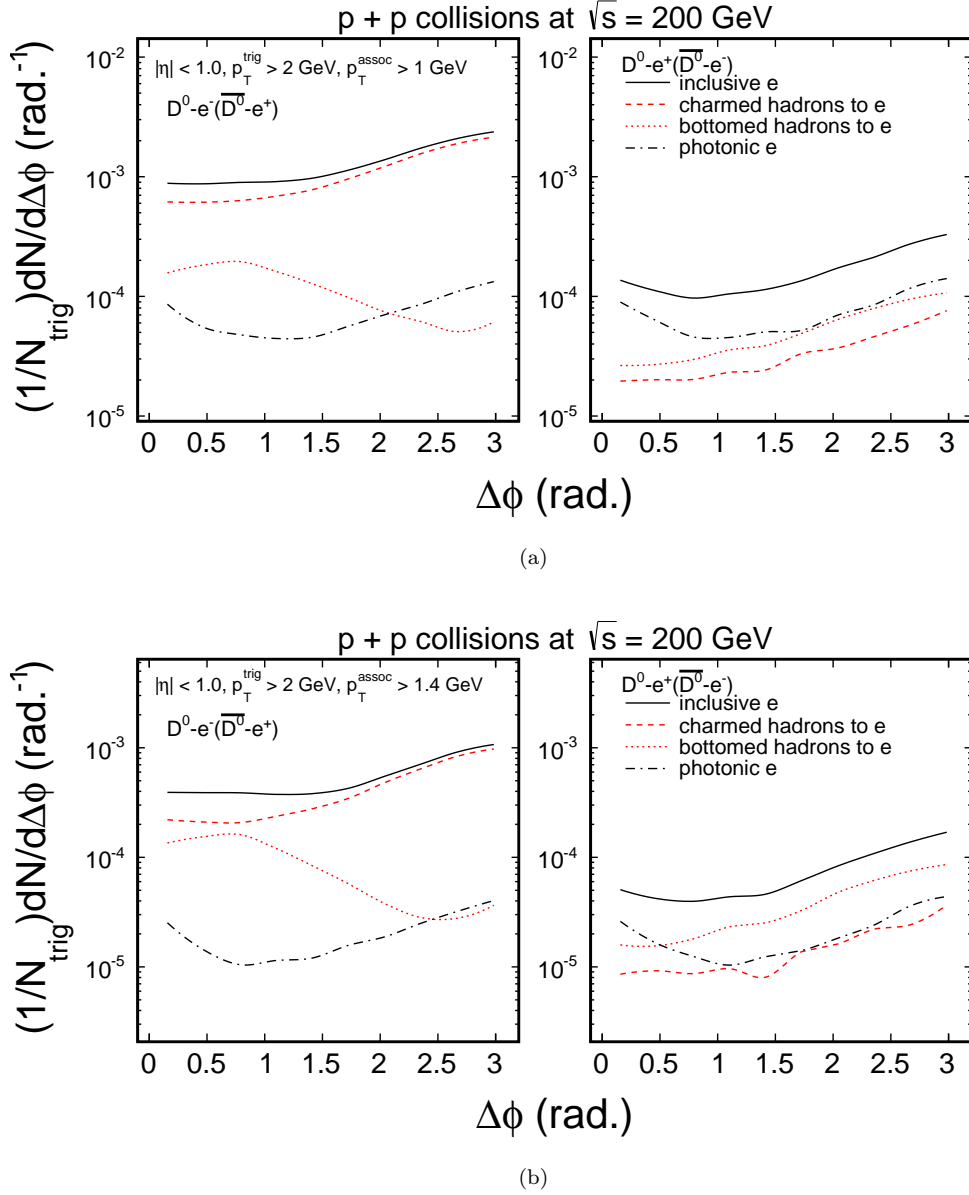


FIG. 4: (Color online) The $D^0-e^- (\bar{D}^0-e^+)$ and $D^0-e^+ (\bar{D}^0-e^-)$ correlations as a function of relative azimuth angle $\Delta\phi$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV. Different lines represent different sources of electron sample. The minimum trigger p_T cut is 2 GeV/c and the minimum associate p_T cut is 1 GeV/c for panel (a) and 1.4 GeV/c for panel (b), respectively.

way, we chose D^0 from golden hadronic decay channel $D^0 \rightarrow K^+ + \pi^-$. Based on the sources of electrons, we plot the correlation of D^0 : 1) to electrons from charmed hadrons, 2) to electrons from bottomed hadrons, 3) to photonic electrons. Note that charmed hadrons contain the direct charm and decay contributions from bottomed hadrons, to be consistent with the experimental capability. The inclusive electrons are simply the sum of all three cases mentioned above. As the low p_T electrons are mainly from photonic sample, a minimum p_T cut is usually applied on electrons. Panel (a) and (b) show the minimum p_T cut of electrons = 1 and 1.4 GeV/c respec-

tively. The initial $c-\bar{c}$ correlations contribute to D^0-e^- and \bar{D}^0-e^+ correlations which are shown in the left panels, where D^0-e^+ and \bar{D}^0-e^- can be interpreted as other contributions which are shown in the right panels. It is clear that the near side correlation pattern of D^0-e^- is mainly from bottom events and the away side correlation pattern of D^0-e^- is mainly from charm events. As discussed in reference [18], the azimuthal correlation of D^0 and non-photonic electrons allows the separation of charm and bottom production on a statistical basis. The D^0 - photonic e^- and D^0 - photonic e^+ correlation pattern are symmetric, because the Dalitz decay or the γ conver-

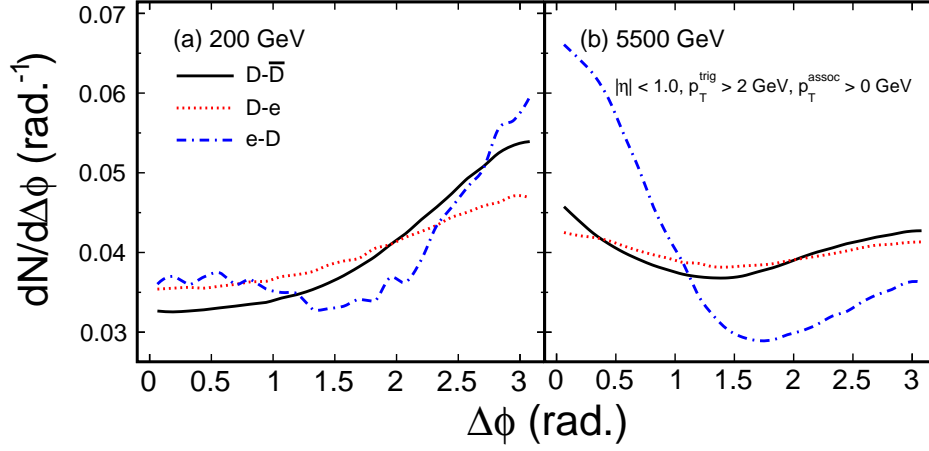


FIG. 5: (Color online) The $D\text{-}\bar{D}$, $D\text{-}e$ and $e\text{-}D$ correlations as a function of relative azimuth angle $\Delta\phi$ in $p + p$ collisions calculated by PYTHIA at (a) $\sqrt{s} = 200$ GeV and (b) 5500 GeV. The integral of correlation function are normalized to one.

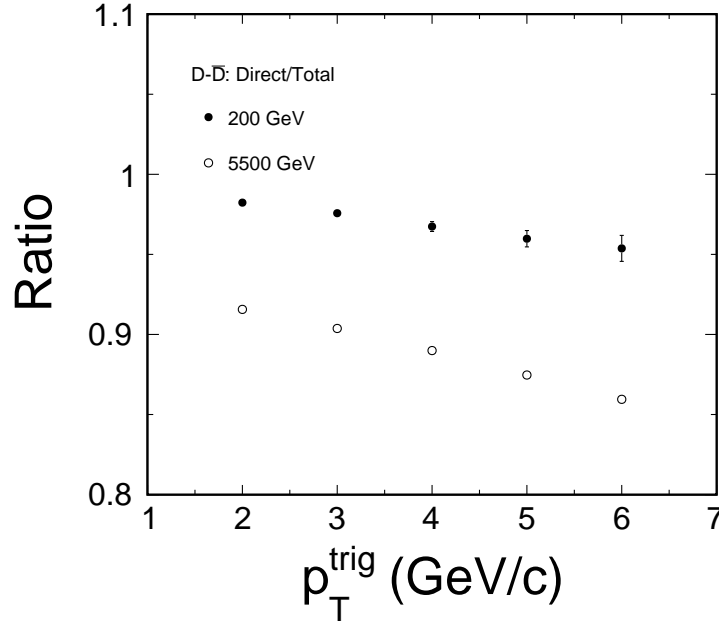


FIG. 6: The ratio of direct $D\text{-}\bar{D}$ pairs to total $D\text{-}\bar{D}$ pairs as a function of trigger transverse momentum in $p + p$ collisions at $\sqrt{s} = 200$ and 5500 GeV.

sion contributes equally to e^+ and e^- . As the minimum p_T cut on electrons increases, the bottom contributions become larger. This can be explained by the increase of $B \rightarrow e$ to $D \rightarrow e$ ratio as a function of p_T [17]. The results of $p + p$ at $\sqrt{s} = 500$ GeV is similar to the 200 GeV results. To investigate the $c\text{-}\bar{c}$ correlations by measuring $D\text{-}e$ correlation, one has to stick to away side region which is dominant by charm contributions. The $\Delta\phi$ region of 2

- π would be fine inferring from PYTHIA simulation.

D. RHIC versus LHC energy

From RHIC to LHC, as the collision energy increases, higher order pQCD and bottom contributions to the correlation functions become more and more significant. In

Fig. 5, we compare the $D\bar{D}$, $D-e$ (non-photonic electrons) and $e-D$ correlations in $p + p$ collisions at $\sqrt{s} = 200$ and 5500 GeV. We chose these two collision energies, as they are the top heavy ion collision energies at RHIC and LHC, respectively. One can observe the near side correlations show almost the same magnitude as the away side correlations for $D\bar{D}$ correlation function at the LHC energy. Furthermore, the higher order pQCD processes smear the away side correlations significantly: in the $D-e$ case, the correlation function is almost flat in $p + p$ collisions at $\sqrt{s} = 5500$ GeV. The large near side peak of $e-D$ correlations are from B to e contributions. Similar as Sec. III B, we separate the $D\bar{D}$ correlations into direct D and B to D correlations. It is found the near side correlations are from B to D contributions. Quantitatively, in Fig. 6, we show the ratio of direct $D\bar{D}$ pairs to total $D\bar{D}$ for 200 and 5500 GeV. It is observed that the $D\bar{D}$ pairs from B contributions are relatively larger in LHC energy than RHIC energy. Up to trigger p_T cut at 6 GeV/ c , the $D\bar{D}$ pairs from B contributions are less than 5% in 200 GeV collisions where the B contribution is $\sim 15\%$ in 5500 GeV collisions. The PYTHIA results suggest that charm correlations might not be the best choice at the LHC energy, as the baseline measurements in $p + p$ are significantly affected by B contributions and higher order pQCD. On the other hand, bottom correlations, especially $B\bar{B}$ correlations are clean probes for both $p + p$ and heavy ion collisions and possible to be done at LHC energies, due to the larger production cross section.

IV. SUMMARY

With PYTHIA (version 8.168) framework, we studied $D\bar{D}$ and $D-X$ ($X-D$) correlations in $p + p$ collisions at

$\sqrt{s} = 200$ and 500 GeV. D -hadron correlation is found to be effected significantly by the jet correlations. $D\bar{D}$ correlation is the ideal choice to approach initial $c\bar{c}$ pair correlations. The bottom decay contributions to $D\bar{D}$ pairs are less than 4% at $p + p$ collisions in $\sqrt{s} = 500$ GeV with trigger p_T cut at 3 GeV/ c , thus it is not significant at RHIC energies. D - non-photonic electron correlation contains both contributions from charm and bottom events. The charm/bottom events dominate the near/away side correlation pattern respectively. D - non-photonic electron correlations can be used to determine the branching ratios for the charm and bottom decays to electrons. One can also study $c\bar{c}$ correlations from the away side pattern of $D-e$ correlation with a proper $\Delta\phi$ cut. The charm quark correlations are found to be less attractive at LHC energies, due to the relatively larger bottom and higher order pQCD contributions. Alternatively, the bottom quark correlations would be applicable at LHC. Experiment measurements on heavy quark (c and b) correlations are crucial to understand the charm correlations in $p + p$ collision system, thus offering precious data to constrain the pQCD calculations. Furthermore, in heavy ion collisions, these measurements are important to investigate the charm-medium interactions and disentangle the contributions of different charm energy loss mechanisms in the hot and dense medium.

V. ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China under grant No. 11475070 and National Basic Research Program of China (973 program) under grand No. 2015CB8569.

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